WISCONSIN HIGHWAY RESEARCH PROGRAM #0092-04-08

APPLICATION OF ELECTROMAGNETIC GEOPHYSICS (EMG) TECHNOLOGY TO SUBSURFACE INVESTIGATIONS

FINAL REPORT

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SUBMITTED TO THE WISCONSIN DEPARTMENT OF TRANSPORTATION

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16. Abstract

A study was performed to investigate current methods for using EMG technology to assess the capabilities, limitations, and costs associated with these methods, and to identify EMG consultants and equipment that may be of benefit to WisDOT for performing site investigations in Wisconsin. Based on the results of this study, six EMG methods were identified and described. Based on the information provided by 10 consultants, several consultants who may be attractive candidates for providing EMG services to WisDOT were identified. Information was also compiled on 17 pieces of EMG equipment manufactured by 7 companies. This report provides a comprehensive overview of EMG in terms of description of methods, synopsis of consultant capabilities, and a summary of available EMG equipment.

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EXECUTIVE SUMMARY

Project Summary

The Wisconsin Department of Transportation (WisDOT) sponsored a research study through the Wisconsin Highway Research Program (WHRP) to investigate current methods for using EMG to assess the capabilities, limitations, and costs associated with these methods. The study was conducted by Dr. Michael E. Kalinski (Investigator) from the University of Kentucky (UK). The study was performed under the direction of the WHRP EMG Research Oversight Committee, including Dan Reid, Robert Arndorfer, and Robert Patenaude from the Wisconsin Department of Transportation, and David Hart from the Wisconsin Geological and Natural History Survey. WisDOT wished to assess the applicability of EMG towards characterizing sites consisting of soil conditions commonly found in Wisconsin, including frozen ground, organic soils, overconsolidated clays, and other soils of glacial origin. With a comprehensive understanding of EMG, WisDOT will be able to judiciously apply EMG to perform non-intrusive site characterization in Wisconsin.

Background

In geotechnical engineering, electromagnetic geophysics (EMG) has been successfully used for numerous applications to non-intrusively assess subsurface conditions. However, there has historically been a lack of communication between geophysicists, whose training and background are focused on geology, math, and physics, and geotechnical engineers, whose training and background are based on a broader spectrum of civil engineering subject matter. As a result, geophysicists do not always effectively describe their technology and methods to their clients, and geophysical methods such as EMG are sometimes perceived as "black box" technologies that are not understood nor trusted by practicing engineers. The problem is exacerbated when overzealous geophysical contractors oversell their methods, and the subsequent results from the geophysical survey are disappointing. Thus, there is a clear need to bridge the communication gap between geophysicists and geotechnical engineers so that geophysical methods such as EMG can be properly applied by geotechnical engineers with successful results.

EMG methods are methods where the response of the earth to an external electromagnetic field is measured to nondestructively and non-intrusively characterize the subsurface. Earth response to an electromagnetic field is primarily dependent upon the bulk electrical conductivity (σ) of the near-surface soil or rock, so EMG methods are used to quantify variations in σ in the subsurface. Use of an EMG method to quantify variations in σ allows different types of subsurface earth materials to be non-intrusively differentiated and delineated. EMG methods have been successfully used for a number of geotechnical applications, including:

- Estimation of pore water salinity;
- Detection and delineation of subsurface voids and karst features;
- Characterization of soil stratigraphy;
- Estimation of depth and lateral extent of frozen earth;
- Delineation of landfills;
- Archaeological studies;
- Location of unexploded ordnance (UXO);
- Assessment of borrow materials;
- Estimation of depth to bedrock;
- Characterization of bedrock fracture patterns;
- Delineation of hydrogeological features;
- Location of buried objects; and
- Contaminant plume mapping.

Process

The objectives of this study were achieved through a 12-month research program that included the following tasks:

- Identify the types of soil conditions commonly encountered in Wisconsin;

- Describe the current state of practice of EMG, including the capabilities and limitations of each method;

- Compile a list of geophysical consultants with capabilities to perform EMG in Wisconsin, along with Statements of Qualification (SOQs), relevant experience, and fee schedules;

- Compile a list of EMG equipment manufacturers, and describe the capabilities, limitations, costs, and training requirements associated with the equipment; and

- Prepare a report detailing the results of the study.

Findings and Conclusions

Summary of EMG Methods. Based on the results of this study, six EMG methods were identified and described. Each method provides different information regarding the subsurface, and is useful for site characterization to different depths. The six methods are described in the report, and include:

- Time-domain electromagnetics (TDEM);
- frequency-domain electromagnetics (FDEM);
- terrain conductivity;
- very low frequency electromagnetics (VLFEM);
- magnetotellurics; and
- capacitively coupled resistivity (CCR).

Summary of EMG Consultant Information. As part of the research study, geophysical consultants with the potential to offer EMG services in Wisconsin were solicited for Statements of Qualifications (SOQs). Names of potential consultants were compiled from advertisements in professional society newsletters and publications. The Investigator also included consultants with whom he has been associated with as a professional geophysicist. Particular emphasis was given to identifying firms that were based in Wisconsin.

A total of 37 consultants were solicited. Consultants were asked to include the following information in their SOQs:

- A list of EMG methods and equipment that they use;

- project descriptions indicating general experience in EMG;
- project descriptions indicating experience in EMG specific to Wisconsin or places with near-surface conditions similar to Wisconsin;
- references to relevant publications demonstrating their expertise in EMG; and
- a generic fee schedule for EMG services, including mobilization costs, data acquisition costs, and data reduction/reporting costs.

Of these 37 consultants, 10 replied with SOQs. Based on the information provided by the consultants, the Investigator developed recommendations for "Short Listing" each firm for future WisDOT projects. The Investigator believes that the consultants included on the Short List will be able to provide the necessary EMG services in a cost-effective manner, and should be given particular consideration for future Requests for Proposals (RFPs). These recommendations are somewhat subjective, but should provide a reasonable basis for identifying prospective EMG consultants for future WisDOT field investigations.

EMG Equipment Manufacturers. As part of the research study, EMG equipment manufacturers were solicited with requests for information regarding their equipment. Names of potential equipment suppliers were compiled from advertisements in professional society newsletters and publications. The Investigator also included manufacturers with whom he has been associated with as a professional geophysicist. Information regarding equipment used by the consultants as described in the SOQs was also actively sought and incorporated into the synthesis.

A total of 20 companies, including equipment manufacturers, data reduction software companies, and equipment lessors, were solicited. All companies were asked to provide the following specific information:

- A list of all new and refurbished EMG equipment that they offer;

- a list of the EMG methods that can be applied using each piece of equipment;
- the costs associated with acquiring, maintaining, and/or leasing the equipment;
- the required software for reducing data acquired using the equipment, and the costs associated with licensing and software training;
- a description of training that they provide to use the equipment, including costs and training schedules; and
- copies of relevant publications describing the applicability of their equipment towards site characterization in general, and specifically in Wisconsin.

Of the 20 companies listed, information was obtained on 17 pieces of EMG equipment manufactured by 7 companies. Descriptions of each instrument manufactured by each company are included. A summary table is also include, which details costs associated with purchase, rental, and training for each piece of equipment, along with the approximate achievable depth of investigation for each method.

Recommendations for Further Study

This study provides a comprehensive overview of EMG in terms of description of methods, synopsis of consultant capabilities, and a summary of available EMG equipment. Fee schedules provided by consultants were generic, so it would be beneficial to perform a direct comparison of the contractors on a specific job. The Investigator recommends that WisDOT identify an opportunity to use EMG for site characterization on a specific project, send out 5-6 Requests for Proposal (RFPs) to short-listed EMG consultants, and select 2-4 consultants to perform field testing. This would serve two purposes: 1) WisDOT would get a direct cost comparison to compare the different consultants, and 2) WisDOT would have an opportunity to work with several EMG consultants to directly assess their performance in terms of quality and responsiveness to the client.

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1. PROBLEM STATEMENT

In geotechnical engineering, electromagnetic geophysics (EMG) has been successfully used for numerous applications to non-intrusively assess subsurface conditions. However, there has historically been a lack of communication between geophysicists, whose training and background are focused on geology, math, and physics, and geotechnical engineers, whose training and background are based on a broader spectrum of civil engineering subject matter. As a result, geophysicists do not always effectively describe their technology and methods to their clients, and geophysical methods such as EMG are sometimes perceived as “black box” technologies that are not understood nor trusted by practicing engineers. The problem is exacerbated when overzealous geophysical contractors oversell their methods, and the subsequent results from the geophysical survey are disappointing. Thus, there is a clear need to bridge the communication gap between geophysicists and geotechnical engineers so that geophysical methods such as EMG can be properly applied by geotechnical engineers with successful results.

Therefore, the Wisconsin Department of Transportation (WisDOT) sponsored a research study through the Wisconsin Highway Research Program (WHRP) to investigate current methods for using EMG to assess the capabilities, limitations, and costs associated with these methods. The study was conducted by Dr. Michael E. Kalinski (Investigator) of the University of Kentucky (UK). The study was performed under the direction of the WHRP EMG Research Oversight Committee, including Dan Reid, Robert Arndorfer, and Robert Patenaude from the Wisconsin Department of Transportation, and David Hart from the Wisconsin Geological and Natural History Survey. WisDOT wished to assess the applicability of EMG towards characterizing sites consisting of soil conditions commonly found in Wisconsin, including frozen ground, organic soils, overconsolidated clays, and other soils of glacial origin. With a comprehensive understanding of EMG, WisDOT will be able to judiciously apply EMG to perform non-intrusive site characterization in Wisconsin. These objectives were achieved through a 12-month research program that included the following tasks:

- Identify the types of soil conditions commonly encountered in Wisconsin;
- Describe the current state of practice of EMG, including the capabilities and limitations of each method;
- Compile a list of geophysical consultants with capabilities to perform EMG in Wisconsin, along with Statements of Qualification (SOQs), relevant experience, and fee schedules;
- Compile a list of EMG equipment manufacturers, and describe the capabilities, limitations, costs, and training requirements associated with the equipment; and
- Prepare a report detailing the results of the study.

The results of this study will help bridge the communication gap between geophysicists and WisDOT by providing a comprehensive understanding of EMG. With this understanding, WisDOT personnel will be able to fully understand the capabilities and limitations of EMG and exploit EMG as a site characterization tool. The primary purpose of any geophysical technology, including EMG, is to minimize the amount of soil borings required by providing indirect information about the subsurface between borings. By effectively applying EMG, WisDOT will i) enhance their ability to characterize sites by acquiring a larger amount of data with a more diverse set of site characterization tools, and ii) reduce costs associated with site characterization studies by minimizing the amount of boreholes required.

2. SOIL CONDITIONS IN WISCONSIN

Wisconsin bedrock consists of Precambrian sedimentary, igneous, and metamorphic rocks, which may be overlain by lower and middle Paleozoic carbonate and clastic sedimentary rocks. Bedrock is overlain by unconsolidated material ranging in thickness from 0-600 ft. Soil deposits are primarily glacial in origin, and include poorly sorted tills, well-sorted outwash sands and gravels, and lacustrine clay deposits (Fig. 1). These glacial deposits, cumulatively referred to as “drift,” range in thickness from 0-300 ft, and cover the entire state with the exception of the “Driftless Area” in the southwest corner (Fig. 2). Physical features include outwash plains, drumlins, eskers, kames, and moraine deposits. There are also extensive deposits of aeolian well-sorted sand and silt (loess) overlying the drift deposits, with thicknesses of up to 16 ft (Fig. 3). Apart from their unique depositional origin, the soils found in Wisconsin are not particularly different than soils found in other states.

The presence of organic soil (i.e. peat) is common to areas that have experienced extensive recent glaciation due to their relatively immature drainage systems, and Wisconsin falls into this category. As a northern state, there is also a significant amount of frozen ground during the winter months. These two conditions (organic soils and frozen ground) are relatively unique to Wisconsin.

Fig. 1 – Extent and Type of Glacial Deposits in Wisconsin

Fig. 2 – Thickness of Glacial Deposits in Wisconsin

Fig. 3 – Aeolian Silt and Sand Deposits of Wisconsin

3. OVERVIEW OF EMG METHODS

3.1. Introduction

EMG methods are methods where the response of the earth to an external electromagnetic field is measured to nondestructively and non-intrusively characterize the subsurface. Earth response to an electromagnetic field is primarily dependent upon the bulk electrical conductivity (σ) of the near-surface soil or rock, so EMG methods are used to quantify variations in σ in the subsurface. Bulk electrical conductivity is defined as:

$$\sigma = \frac{L}{RA}, \tag{1}$$

where, R is the electrical resistance measured across a prismatic shape with length L and cross-sectional area A as illustrated in Fig. 4.

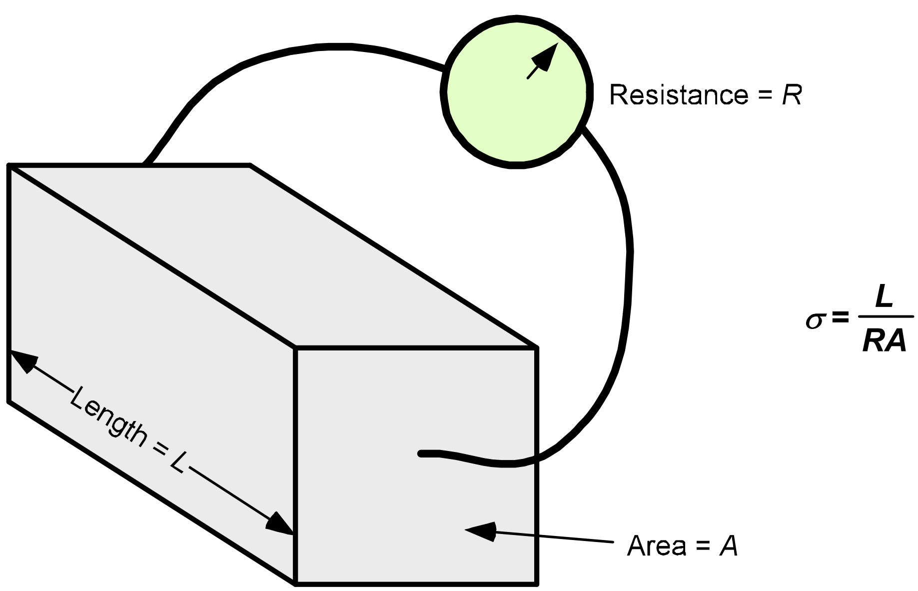

Fig. 4 – Definition of bulk electrical conductivity, σ

Electrical conductivity is expressed in units of conductance per length. Conductance is expressed in units of Seimens or mhos, and 1 Seimen is equal to 1 mho. Thus, σ is expressed in units of S/m or mho/m. Electrical resistivity, ρ, is the reciprocal σ, and is expressed in units of resistance times length (i.e. ohm-m). Note that resistance is the reciprocal of conductance. Different types of earth materials possess different electrical conductivities as summarized in Table 1.

Table 1—Typical values for bulk electrical conductivity in soil and rock (Reynolds, 1997; USACE, 1995)

Material	**Typical Range in Values (mS/m)**
Igneous Rocks	$10^{-3} – 10^{1}$
Metamorphic Rocks	$10^{-3} – 10^{1}$
Limestone	$10^{-3} – 10^{1}$
Sandstone	10^{-6} - 10^{3}
Shale	10^{0} - 10^{3}
Dry Clay	$10^{0} – 10^{1}$
Saturated Clay	10^{1} - 10^{3}
Dry Sand	$10^{0} – 10^{1}$
Saturated Sand	$10^{1} – 10^{2}$
Permafrost	$10^{-1} – 10^{0}$

Use of an EMG method to quantify variations in σ allows different types of subsurface earth materials to be non-intrusively differentiated and delineated. As indicated in Table 1, there is a wide range in values for σ for a given type of material. The bulk electrical conductivity of soil, σ, is dependent upon several parameters, including volumetric water content (θ), electrical conductivity of the pore fluid, σ_w, electrical conductivity of the soil matrix, σ_s, and soil texture (i.e. flow path tortuosity). For example, Rhodes et al. (1976) expressed σ in undisturbed fine-grained soils as:

$$\sigma = \sigma_w \left(a\theta^2 + b\theta\right) + \sigma_s \, . \tag{2}$$

In Eqn. 2, a and b are soil-specific regression coefficients that are typically on the order of 1 and 0, respectively. Soil matrix conductivity, σ_s, is typically on the order of 10^0 mS/m. Pore fluid conductivity, σ_w, typically ranges from $10^1 - 10^3$ mS/m, depending on pore fluid hardness. Volumetric water content (θ) is defined as the volume of water (V_w) per unit volume of soil (V):

$$\theta = \frac{V_w}{V}. \tag{3}$$

The large variation in σ for a given material is largely due to the dependence of σ on σ_w. Two identical materials with different types of pore fluid can have measured values for σ that vary by orders of magnitude depending on the nature of the pore fluid. Thus, measurement of σ using an EMG method also provides information about the nature of the pore fluid.

EMG methods have been successfully used for a number of geotechnical applications, including:

- Estimation of pore water salinity;
- Detection and delineation of subsurface voids and karst features;
- Characterization of soil stratigraphy;
- Estimation of depth and lateral extent of frozen earth;
- Delineation of landfills;
- Archaeological studies;
- Location of unexploded ordnance (UXO);
- Assessment of borrow materials;
- Estimation of depth to bedrock;
- Characterization of bedrock fracture patterns;
- Delineation of hydrogeological features;
- Location of buried objects; and
- Contaminant plume mapping.

EMG methods can be active, where the earth response to a man-made electromagnetic field is measured, or passive, where the earth response to a naturally occurring or ambient electromagnetic field is measured. An EMG method that quantifies variations in σ with depth is referred to as a sounding method, while an EMG method that quantifies lateral variations in σ is referred to as a profiling method. EMG methods commonly described in literature (Reynolds, 1997; USACE, 1995; ASCE, 1998; FHWA, 2003) and applied today are summarized in the following sections. Note that for the purposes of this study, only non-intrusive surface-borne methods are considered. Airborne and borehole methods are not included in the discussion. Furthermore, discussion of Ground Penetrating Radar (GPR) has been excluded at the request of WisDOT because of their existing expertise in GPR testing.

3.2. Time-Domain Electromagnetics

TDEM involves the use of an outer transmitter and an inner receiver coil oriented coaxially and laid flat on the ground surface (Fig. 5). A square wave with a frequency on the order of 1-100 Hz is passed through the transmitter coil, which establishes a magnetic field in the subsurface. When the current in the transmitter coil is shut off, the collapse of the magnetic field induces a time-dependent voltage in the smaller receiver coil. Voltage is measured as a function of time in the receiver coil during this shutoff period, which is on the order of milliseconds.

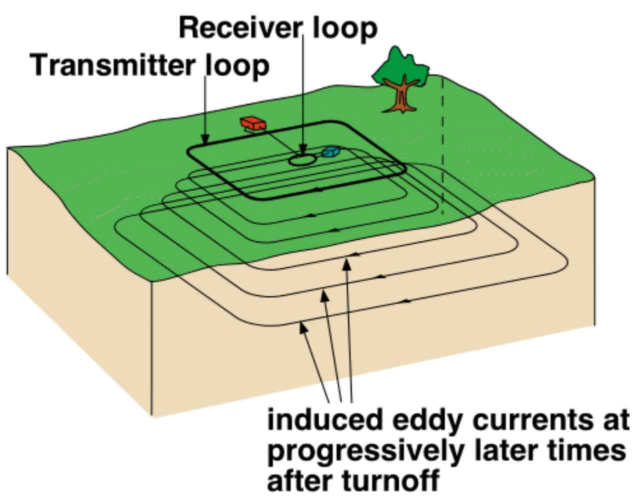

Fig. 5 – TDEM field acquisition system

Variations in voltage with time are caused by variations in σ with depth in the subsurface. Shallower materials affect the voltage-time curve at earlier stages in the reading, while deeper materials affect the voltage-time curve at later stages in the reading. The voltage-time data are inverted to quickly (within a few minutes) derive a sounding of σ versus depth. Depth of investigation is on the order of the transmitter coil size, which may be up to hundreds of meters using equipment available on the market today.

TDEM can provide excellent lateral resolution when adjacent soundings are used. With the TDEM method, measured voltage is proportional to $\sigma^{1.5}$, which is in contrast to other methods where voltage measured in a receiver coil is proportional to $\sigma^{1.0}$. Thus, TDEM field measurements are intrinsically more sensitive to subsurface variations in σ. However, TDEM generally performs poorly in resistive material.

3.3. Frequency-Domain Electromagnetics

Frequency-domain electromagnetics (FDEM) is a method where the earth is excited over a range in frequencies (from 100s of Hz to 10s of kHz), and the response is measured as a function of frequency. It is performed using a transmitter and receiver coil spaced a distance *s* apart. The coils are coplanar, and can be oriented either horizontally (vertical dipole mode; a.k.a. slingram) or vertically (horizontal dipole mode) as shown in Fig. 6. The transmitter coil is excited with a sinusoidal electrical signal of frequency *f*. The oscillating signal induces an electromagnetic field in the subsurface which is detected by the receiver coil, and the strength of the induced signal is related to σ of the subsurface material. The signal induced in the subsurface is referred to as the secondary signal, but the signal detected by the receiver coil is a superposition of the secondary signal and a primary signal that results from direct induction between the transmitter and receiver coils. Since the secondary signal is of interest in characterizing the subsurface, the primary signal is mathematically subtracted from the detected signal.

Fig. 6 – FDEM field data acquisition configuration (shown in horizontal dipole mode)

With respect to EMG, depth of investigation can be quantified in terms of the skin depth. Skin depth, δ, is defined in units of meters as the depth of influence of an electromagnetic wave of frequency f (in units of Hz) in a material with bulk electrical conductivity σ (in units of S/m):

$$\delta = \sqrt{\frac{1}{\sigma \pi f}} \; . \tag{4}$$

As indicated in Eqn. 4, skin depth is inversely proportional to f. Lower frequencies correspond to longer wavelengths that penetrate deeper into the layered system. Higher frequencies, on the other hand, correspond to shorter wavelengths that do not penetrate as deep. Therefore, skin depth can be related to f. To quantify σ, the field equipment is calibrated such that the relationship between signal strength detected in the receiver and the product of conductivity and frequency is linear. By exciting at a given frequency, and knowing the strength of the measured signal, σ can also be related to f. Using these two relationships (skin depth versus f and σ versus f), a relationship of σ versus skin depth can be developed, which can be inverted to quantify variations in σ with depth in a layered system. Therefore, FDEM can be used as a sounding tool.

FDEM can also be used as a tool to identify the top of buried conductive objects (e.g. drums). By gradually decreasing the operating frequency, the frequency at which an anomaly appears can be associated to the depth to the top of the anomaly using the concept of skin depth.

Historically, FDEM testing has been performed using coils at varying spacings. Coils were tuned to a specific frequency, so each spacing corresponded to a specific frequency, and a different set of coils was used for each spacing. However, improvements to equipment have led to superior systems that consist of a pair of receivers spaced a few meters apart (Won et al., 1996). Increased dynamic range, improved primary-field rejection algorithms, and use of coils with very high tuning frequencies, have allowed such instrumentation to be developed. This new approach to FDEM testing is an improvement because equipment is more portable (weighing around 10 pounds) and data acquisition is much faster (10,000 field measurements per hour, which each measurement containing a full bandwidth of information for derivation of a sounding). One limitation of the newer systems is that they can only characterize σ to a depth of around 50 m, while older systems can characterize σ to a depth on the order of hundreds of meters.

3.4. Terrain Conductivity

Terrain conductivity testing involves the use of a coplanar transmitter and receiver coil (either vertical or horizontal in orientation) with a fixed spacing. The field acquisition configuration is similar to that used for FDEM testing. By driving the transmitter coil at a low frequency (on the order of 1-10 kHz) such that the skin depth is much greater than the coil spacing, the voltage generated in the receiver coil is proportional to the average electrical conductivity of the near-surface material (McNeill, 1980). Under these conditions, the measured signal, σ can be calculated based on the measurement of H_s/H_p (where H_s and H_p are the secondary and primary signals, respectively):

$$\sigma \cong \frac{2}{\mu_o \pi f s^2}\left(\frac{H_s}{H_p}\right), \tag{5}$$

where f is frequency, s is the coil spacing and μ_o is the electrical permeability of free space (a constant). Terrain conductivity meters can be operated using either horizontal loops (vertical dipole mode) or vertical loops (horizontal dipole mode). Conductivity measured using the terrain conductivity method represents the average conductivity of the near-surface material to a depth that is approximately equal to 1.5 and 0.75 times the coil spacing for vertical and horizontal dipole operation, respectively. This depth ranges from 0.75-60 m using commercial equipment available today.

Terrain conductivity is a rapid method for acquiring large amounts of data with little data reduction effort. Field equipment is calibrated to directly read in units of conductivity, and measurements are made instantaneously at the push of a button. Field equipment is highly portable and typically resembles PVC pipe a few meters in length. Terrain conductivity is a profiling tool that can be used to delineate lateral variations in σ. However, the method does not allow variations in σ with depth to be quantified.

3.5. Very Low Frequency Electromagnetics

Very low frequency electromagnetics (VLFEM) is a passive method that relies on ambient low-frequency (15-25 kHz) military submarine radio signals to induce magnetic fields in long conductive bodies, such as fluid-filled joints and ore dikes. Data are acquired using small hand-held perpendicularly oriented coils. VLFEM is most appropriate for geological prospecting for conductive ore bodies, but may also be useful for delineating long linear features such as tunnels. Bodies with depths of up to 20 m can typically be delineated. The method works best when the target is relatively conductive, and the surrounding host material is relatively resistive.

3.6. Magnetotellurics

The magnetotelluric method is a passive method where an electromagnetic field on the order of 10 Hz to 100 kHz generated by lightning and solar winds is measured. Orthogonal electrical and magnetic fields are measured. Small coils are used to measure the magnetic field, while porous pots with spacings on the order of thousands of feet are used to measure the electric field. The induced electromagnetic field is measured as a function of frequency. The measured data are used calculate σ as a function of frequency, and this information is inverted to calculate σ as a function of depth. The magnetotelluric method is generally used as a large-scale geologic reconnaissance tool, and depth of investigation up to 1,000 m can be achieved.

3.7. Capacitively Coupled Resistivity

Capacitively couple resistivity (CCR) is a relatively new method that mimics conventional DC resistivity surveying to produce a two-dimensional cross-section of σ. Conventional DC resistivity surveying involves the use of a pair of source electrodes across which a current, I, is applied, and a pair of receiver electrodes across which a voltage, V, is measured (Fig. 7).

When the current is applied, a static electrical field is established in the ground. The shape of the electrical field and, hence, V, are affected by variations in σ in the subsurface. Apparent conductivity, σ_a, is calculated using the relationship:

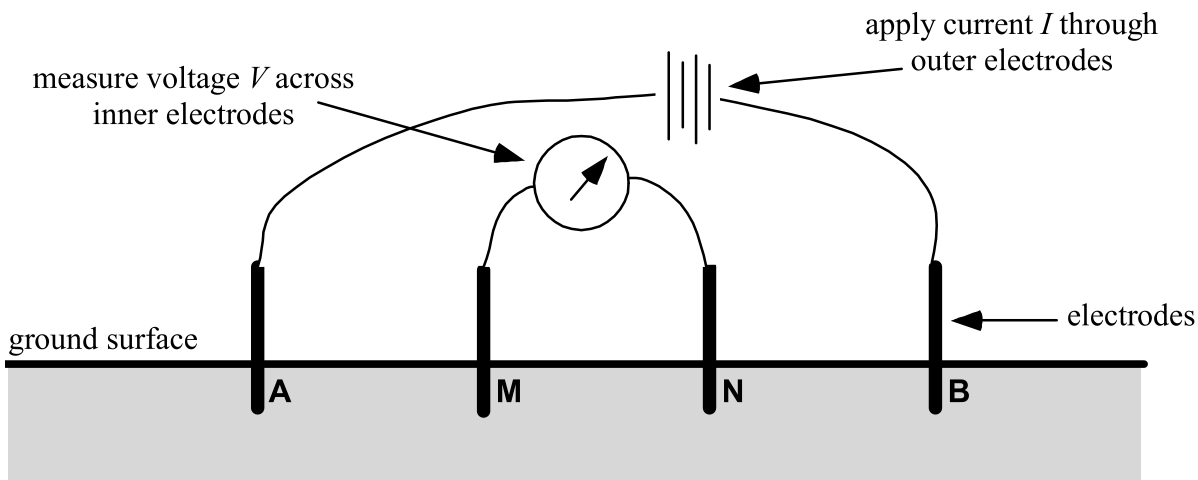

Fig. 7—Electrode arrays for traditional DC conductivity surveying

$$\sigma_a = \frac{KI}{2\pi V}. \tag{6}$$

In. Eqn. 6, K is an array geometry factor:

$$K = \frac{1}{\frac{1}{AM} + \frac{1}{BN} - \frac{1}{BM} - \frac{1}{AN}}, \tag{7}$$

where AM, BN, BM, and AN are distances between the four electrodes as labeled in Fig. 7. By performing measurements at different portions along a line using different electrode spacings, a pseudo-cross section of σ_a versus position and electrode spacing is created. Larger electrode spacings correspond to deeper penetration, so the pseudo-cross-section can be inverted to derive a cross section of σ within the subsurface (Loke and Barker, 1996).

Conventional DC resistivity surveying using metal electrodes is a popular method, but possesses some limitations. The use of electrodes significantly increases the time required for data acquisition. In areas with highly resistive surface material, such as arid climates or permafrost, it can be difficult to achieve intimate electrical contact between the electrodes and the ground, which compromises data quality.

As an alternative to DC resistivity profiling using electrodes, the CCR method was developed (Timofeev et al., 1994). In the CCR method, each current electrode (*A* and *B*) is replaced with a conductor pair that is electrically insulated from the ground (Fig. 8). When an alternating current voltage (approximately 16 kHz) is applied across the conductor pair, each conductor pair acts as a pair of capacitors. Charges are established in the ground, which induce current. The voltage electrodes (*M* and *N*) are replaced with the same type of conductor pairs, and voltage is measured using the same principle. Thus, the spacing of the conductor pairs can be varied in the same way that electrode spacing is varied in conventional DC resistivity surveying to derive a pseudo-cross section, which can be subsequently inverted to derive a profile showing variations in σ with depth and lateral position.

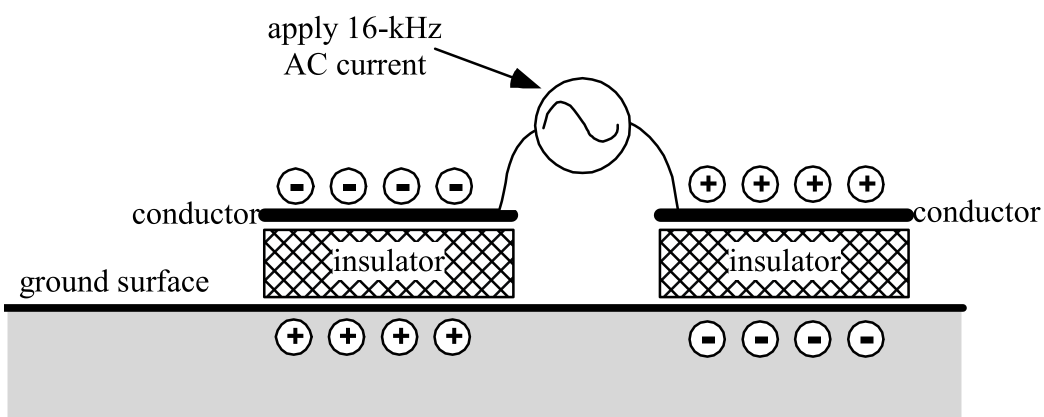

Fig. 8—Conductor pair used in CCR surveying

By eliminating the need for electrodes, data acquisition using the CCR method is much faster than conventional DC resistivity surveying, and high-quality data can be acquired in areas with highly resistive near surface materials. Furthermore, the equipment can be dragged along the ground surface as a streamer, which expedites measurements. Like DC resistivity surveying using electrodes, the depth of investigation using CCR is roughly one third the maximum electrode spacing.

3.8. Applicability of EMG to Transportation Problems in Wisconsin

With respect to site characterization for transportation infrastructure, each project presents a unique set of problems and challenges, and each project should be considered on an individual basis when deciding whether or not to use EMG technology. When deciding whether or not EMG technology is applicable to a specific project, it is important to understand exactly what is measured using EMG. EMG technology is generally applicable for quantifying vertical and lateral variations in σ in near-surface (less than 50 m deep) earth materials. As summarized in Table 2, some EMG methods are better suited for quantifying lateral variations in σ, while other methods are better suited for quantifying variations in σ with depth. The different methods also have different capabilities with respect to depth of investigation. Therefore, the geological and geotechnical nature of each problem should be considered. For example, EMG would be applicable for a project that requires delineation of groundwater impacted with inorganic contaminants because there would be large contrasts in σ associated with the contaminant. Different EMG technologies would be applicable depending on the required depth of characterization. On the other hand, a project that requires estimation of the density of earth materials would not lend itself to EMG technology because density is not directly related to σ.

Apart from the presence of organic soils and frozen ground, soil conditions in Wisconsin are not particularly different than those encountered in other regions where EMG has been successfully applied, so EMG is also applicable in Wisconsin. However, EMG has also been used on frozen ground and in organic soils, and is applicable towards these unique conditions.

Table 2—Summary of the EMG methods described in this report

Method	Result of Survey	Typical depth of investigation	Data Reduction
TDEM	σ versus depth at a point	< 500 m	must invert field data
FDEM	σ versus depth at a point	< 150 m	must invert field data
Terrain Conductivity	average conductivity from the near surface	< 60 m	must plot raw data to identify anomalies
VLFEM	delineation of long, conductive objects	< 20 m	must plot raw data to identify anomalies
Magnetotellurics	σ versus depth at a point	< 1000 m	must invert field data
CCR	two-dimensional σ cross section	< 20 m	must invert field data

3.9. Summary

Each of the six methods is summarized in Table 2 for quick comparison. As indicated, different methods produce different results, with some methods being sounding methods and some methods being profiling methods. Typical depths of investigation using commercially available equipment are also given. Finally, comments regarding data reduction needs are given. Some methods require inversion of the raw field data, while other methods simply require plotting and qualitative assessment of the data.

4. SYNTHESIS OF EMG CONSULTANT INFORMATION

4.1. Introduction

As part of the research study, geophysical consultants with the potential to offer EMG services in Wisconsin were solicited for Statements of Qualifications (SOQs). Names of potential consultants were compiled from advertisements in professional society newsletters and publications. Professional organizations such as the Environmental and Engineering Geophysical Society (EEGS), Society of Exploration Geophysicists (SEG), and the American Society of Civil Engineers (ASCE) Geo-Institute, are all active in the area of engineering geophysics, and their newsletters and publications were used as sources for consultant information. The Investigator also included consultants with whom he has been associated with as a professional geophysicist. Particular emphasis was given to identifying firms that were based in Wisconsin.

A total of 37 consultants (Table 3) were solicited. SOQs were limited in length to 20 pages. Consultants were asked to include the following information in their SOQs:

- A list of EMG methods and equipment that they use;
- project descriptions indicating general experience in EMG;
- project descriptions indicating experience in EMG specific to Wisconsin or places with near-surface conditions similar to Wisconsin;
- references to relevant publications demonstrating their expertise in EMG; and
- a generic fee schedule for EMG services, including mobilization costs, data acquisition costs, and data reduction/reporting costs.

Of these 37 consultants, 10 replied with SOQs. Each consultant is described in the following sections, and SOQs are included in the CD-ROM at the end of this report (with the exception of Blackhawk Geoservices, who did not submit an electronic SOQ).

Table 3 – Consultants receiving a Request for SOQ for this study

Consultant	Location	Contact Individual	Company web site/contact information
Aquifer Science Technology*	Waukesha, WI	John Jansen	web: www.ruekert-mielke.com
Blackhawk Geoservices*	Golden, CO	Merrie Martin Jones	web: www.blackhawk.com
COLOG Division - Layne Christensen	Golden, CO		web: www.colog.com
Consoer Townsend Envirodyne*	Brookfield, WI	Raye Lahti	tel: (262) 784-4867
Enviroscan*	Lancaster, PA	Felicia Bechtel	web: www.enviroscan.com
General Engineering Geophysics	Oxford, MD		web: www.gel.com
Geological Survey of Canada	Ottawa, ON	Regis Dumont	email: rdumont@nrcan.gc.ca
Geophex, Ltd.	Raleigh, NC		web: www.geophex.com
GeoTrans, Inc.	Brookfield, WI		tel: (262) 792-1282
GeoVision	Corona, CA	Tony Martin	web: www.geovision.com
Golder Associates, Ltd.	Mississauga, ON		web: www.goldergeophysics.com
Hager GeoScience, Inc.	Woburn, MA		web: www.hagergeoscience.com
Hager-Richter Geoscience, Inc.*	Salem, NH	Gene Simmons	web: www.hager-richter.com
Harding Lawson Associates	Portland, ME		tel: (207) 775-5401
HydroGEOPHYSICS, Inc.	Tucson, AZ		web: www.hydrogeophysics.com
INEEL	Idaho Falls, ID		web: subsurface.inel.gov
Komex International	Saskatoon, SK	Bruce Reiter	web: www.komex.com
Layne-Northwest	Pewaukee, WI	Dan Peplinski	email: 1060@laynechristensen.com
Mactec*	Oakland, CA	Roark Smith	email: rwsmith@mactec.com
Naeva Geophysics*	Charlottesville, VA	John Allan	www.naevageophysics.com
Norcal Geophysical Consultants	Petaluma, CA	William Black	email: wblack@norcalgeophysical.com
Ohio State University	Columbus, OH	Jeff Daniels	email: jeff@geology.ohio-state.edu
P.E. LaMoreau & Associates	Oak Ridge, TN	Barry Beck	email: info@pela-tenn.com
Schnabel Engineering Associates	Greensboro, NC	Edward Billington	www.schnabel-eng.com
Shaw Environmental and Infrastructure	Houston, Texas	Finn Michelsen	tel: (281) 368-4445
Spectrum Geophysics	Santa Ana, CA	Laura Cathcart-Dodge	web: www.spectrum-geophysics.com
STS Consultants*	Vernon Hills, IL	Craig Padar	email: padar@stsltd.com
SubSurface Surveys	Solano Beach, CA		web: www.subsurfacesurveys.com
Sunbelt Geophysics	Albuquerque, NM		tel: (505) 266-8717
Technos, Inc.	Miami, FL	Richard Benson	www.technos-inc.com
TEG Rocky Mountain	Golden, CO		tel: (303) 278-0104
Terra Physics	Highland, CA	Kerry Hennon	tel: (909) 862-0626
University of Nevada at Las Vegas	Las Vegas, NV	Barbara Luke	email: bluke@ce.unlv.edu
University of Wisconsin	Madison, WI	Dante Fratta	email: fratta@wisc.edu
USDA – NRCS	Newton Square, PA	James Doolittle	email: jdoolittle@fs.fed.us
Western Michigan University	Kalamazoo, MI	William Sauck	email: sauck@wmich.edu
Zonge Engineering and Research*	Tucson, AZ	Kenneth Zonge	web: www.zonge.com

*replied to the Investigator with an SOQ

4.2. Synthesis of Information Received from Consultants

4.2.1. Aquifer Science and Technology

Aquifer Science and Technology (AST) is based in Waukesha, Wisconsin, and their point of contact is John Jansen (Wisconsin Professional Geologist). AST works primarily in the Great Lakes region, so they are experienced with the soil types commonly found in Wisconsin. Most of their efforts are towards aquifer characterization, and many of their clients have been local municipalities who are looking for drinking water supplies. They are experienced in applying a wide range of EMG methods, including FDEM, TDEM, VLFEM, magnetotellurics, and terrain conductivity.

4.2.2. Blackhawk Geoservices

Blackhawk Geoservices is based in Golden, Colorado, and their point of contact is Merrie Martin-Jones. Blackhawk is probably the largest geophysical consultant in the United States, with a broad range of experience. They are particularly strong in application of geophysics and EMG towards transportation problems, and authored the recent FHWA guidance document on the subject (FHWA, 2003). They are experienced in applying a wide range of EMG methods, including TDEM, VLFEM, magnetotellurics, and terrain conductivity. However, it is the Investigator's experience that the costs for their services tend to run high compared to other consultants.

4.2.3. Consoer Townsend Envirodyne

Consoer Townsend Envirodyne (CTE) is based in Chicago, Illinois, and their point of contact is Raye Lahti (Wisconsin Professional Geologist). CTE works in the Great Lakes region, and has experience in the soil types commonly found in Wisconsin. They are experienced in applying a wide range of EMG methods, including TDEM, FDEM, VLFEM, and terrain conductivity towards a number of different geotechnical problems.

4.2.4. Enviroscan

Enviroscan is based in Lancaster, Pennsylvania, and the point of contact is Felicia Bechtel. Enviroscan has experience performing EMG testing in glacial soils similar to those found in Wisconsin. They have experience in applying several methods, including TDEM, VLFEM, terrain conductivity, and CCR. Of the 10 consultants who submitted SOQs, Enviroscan was the only one with experience in CCR.

4.2.5. Hager-Richter Geoscience

Hager-Richter Geoscience is based in Salem, New Hampshire, and the point of contact is Gene Simmons. Hager-Richter also has experience working in northern soils of glacial origin (New England), but has limited expertise in the EMG methods that they apply. Hager-Richter has experience in applying VLFEM and terrain conductivity.

4.2.6. Mactec

Mactec is a large national engineering consulting firm, with EMG services performed out of their Oakland, California office. Their point of contact is Roark Smith. They have experience in a wide range of EMG methods, including TDEM, FDEM, magnetotellurics, and terrain conductivity. They have particularly strong experience in using EMG to characterize permafrost, frozen ground, and organic soils in Alaska, which is the primary reason they were included in this study. Since they are located in California, their mobilization costs are relatively high.

4.2.7. Naeva Geophysics

Naeva Geophysics is based in Charlottesville, Virginia, and their point of contact is John Allan. They have experience in a wide range of EMG methods, including TDEM, FDEM, VLFEM, and terrain conductivity. They have used EMG for numerous applications and for numerous clients, but do not have specific experience in glacial soils similar to those found in Wisconsin.

4.2.8. Shaw Environmental and Infrastructure

Shaw Environmental and Infrastructure is based in Houston, Texas, and their point of contact is Finn Michelsen. They are particularly strong in the field of UXO detection, but have limited expertise in applying a variety of EMG methods (they only list VLFEM and TC as methods that they use). Since they are in Houston, their mobilization costs are relatively high.

4.2.9. STS Consultants

STS Consultants is also a large national engineering consulting firm, with geophysical services offered out of their Chicago, Illinois office. The point of contact is Bridget Calhoun. Their office is relatively local, but they only offer terrain conductivity testing.

4.2.10. Zonge Engineering and Research

Zonge Engineering and Research is based in Tucson, Arizona, and their point of contact is Kenneth Zonge. Zonge is very active in research-based studies, and have developed their own specialized EMG equipment. They are particularly strong in UXO detection, but only use a limited number of EMG methods (TDEM and magnetotellurics). Since they are located in Arizona, their mobilization costs are very high.

4.3. Summary

Table 4 is a summary of each of the consultants and the methods that they offer. Part of this study also included comparison of generic consultant fees. These fees are summarized in Table 5. Note that the fees listed in Table 5 are generic only, and not all consultants provided the same type of information. To get a true comparison between consultants, a fee quote should be obtained for a specific project. Inspection of Tables 4 and 5 reveals some important observations:

- Enviroscan is the only consultant that offers CCR testing. CCR is the only EMG method that allows two-dimensional conductivity cross-sections to be derived, which makes it a relatively unique and attractive method.

- Hager-Richter and STS cannot perform soundings using their methods. For instances where it is necessary to quantify variations in conductivity with depth, these firms will not have the expertise to perform the measurements.

- Hager-Richter, STS, and Zonge use a relatively limited number of EMG methods. It is very beneficial to use more than one geophysical method for site characterization to provide redundancy and constrain the subsurface interpretation. Access to a limited number of methods may result in a subsurface interpretation that is less reliable.

- Mobilization costs for Mactec, Shaw, and Zonge are relatively high due to their geographical locations. Mobilization costs provided by CTE are also high, but these figures are generic. It is likely that for a specific project, mobilization costs for CTE would be less.

Based on the information presented in Section 4 of this report, the Investigator has developed recommendations for "Short Listing" each firm for future WisDOT projects. Each firm is listed in Table 6, along with a Short List recommendation and the primary rationale behind the recommendation. The Investigator believes that the consultants included on the Short List will be able to provide the necessary EMG services in a cost-effective manner, and should be given particular consideration for future Requests for Proposals (RFPs). These recommendations are somewhat subjective, but should provide a reasonable basis for identifying prospective EMG consultants for future WisDOT field investigations.

Table 4—List of EMG consultants and test methods offered

Consultant	FDEM	TDEM	VLFEM	Magnetotellurics	Terrain Conductivity	CCR
AST	x	x	x	x	x	
Blackhawk		x	x	x	x	
CTE	x	x	x		x	
Enviroscan		x	x		x	x
Hager-Richter			x		x	
Mactec	x	x		x	x	
Naeva	x	x	x		x	
Shaw		x			x	
STS					x	
Zonge		x		x		

Table 5—List of EMG consultants and generic fees

Consultant	Principal ($/hr)	Field Tech ($/hr)	Field Costs ($/day)	Reporting Costs ($/day)	Mob/demob ($/job)	Equipment ($/day)
AST	129	66				cost
Blackhawk	150	50				50-400
CTE	125	70	2400	1200	3200	
Enviroscan	no information provided					
Hager-Richter	$2000-3000 per day for the entire project					
Mactec			2200	1300	3700	
Naeva			2200	600	2500	250-400
Shaw	110	45		1000	cost + 10%	75-200
STS	150	65			cost + 10%	200
Zonge	130	45			8000	600

Table 6—Short list recommendations for each EMG consultant

Consultant	Short List	Rationale
AST	yes	regional firm with experience using several EMG methods
Blackhawk	yes	experience using several EMG methods; particularly knowledgeable in transportation-related applications
CTE	yes	regional firm with experience using several EMG methods
Enviroscan	yes	experience using several EMG methods; only firm offering CCR services
Hager-Richter	no	limited experience in using different EMG methods
Mactec	maybe	high mobilization costs, but particularly strong in characterizing frozen ground and permafrost
Naeva	yes	experience using several EMG methods
Shaw	no	limited experience in using different EMG methods; high mobilization costs
STS	no	limited experience in using different EMG methods
Zonge	no	limited experience in using different EMG methods; high mobilization costs

5. SYNTHESIS OF EMG EQUIPMENT MANUFACTURER INFORMATION

5.1. Introduction

As part of the research study, EMG equipment manufacturers and vendors were solicited with requests for information regarding their equipment. Names of potential equipment suppliers were compiled from advertisements in professional society newsletters and publications. Professional organizations such as the Environmental and Engineering Geophysical Society (EEGS), Society of Exploration Geophysicists (SEG), and the American Society of Civil Engineers (ASCE) Geo-Institute, are all active in the area of engineering geophysics, and their newsletters and publications were used as sources for equipment manufacturer information. The Investigator also included manufacturers with whom he has been associated with as a professional geophysicist. Information regarding equipment used by the consultants as described in the SOQs was also actively sought and incorporated into the synthesis.

A total of 20 companies (Table 7), including equipment manufacturers, data reduction software companies, and equipment lessors were solicited. Information packages were limited in length to 30 pages. All manufacturers were asked to provide the following specific information:

- A list of all new and refurbished EMG equipment that they offer;
- a list of the EMG methods that can be applied using each piece of equipment;
- the costs associated with acquiring, maintaining, and/or leasing the equipment;
- the required software for reducing data acquired using the equipment, and the costs associated with licensing and software training;
- a description of training that they provide to use the equipment, including costs and training schedules; and

- copies of relevant publications describing the applicability of their equipment towards site characterization in general, and specifically in Wisconsin.

Of the 20 companies listed in Table 7, information was obtained for 17 instruments manufactured by 7 of these companies as detailed in the following sections. Information obtained electronically from each company is included in the CD-ROM at the end of this report.

5.2. Synthesis of Information Received from Equipment Manufacturers

5.2.1. Apex

Overview. Apex Parametrics of Uxbridge, Ontario was not originally contacted by the Investigator as part of this study and is not included in Table 7. However, their FDEM instrument, the MaxMin, was mentioned by several of the consultants, so discussion of the MaxMin is included herein.

MaxMin I-8. The MaxMin I-8 FDEM system is an FDEM system that allows variations in σ with depth to be quantified to a depth of about 200 m. The I-8 system consists of a set of 11 coils used at different spacings that vary from 12.5-400 m, and a transmitting system that operates at 8 frequencies from 110 to 14,080 Hz. By operating using the different coil spacings and frequencies, apparent conductivity is determined as a function of frequency, which is inverted to derive variations in σ with depth. Measurements using a given coil spacing are affected by material from the ground surface to a depth that is roughly equal to the coil spacing, depending on whether the coils are oriented horizontally or vertically. However, variations in σ with depth can be reliably quantified to a depth less than one-half of the maximum coil spacing.

Table 7 – Companies receiving a Request for Information letters as part of this study

Company Name	Primary Business	Business Location	Internet Web Site
ABEM	Equipment Manufacturer	Sundbyberg, Sweden	www.abem.com
R. T. Clark Co., Inc.	Equipment Rental	Oklahoma City, Oklahoma	www.rtclark.com
Crone Geophysics	Equipment Manufacturer	Mississauga, Ontario	www.cronegeophysics.com
Exploration Instruments	Equipment Sales and Rental	Austin, Texas	www.expins.com
GEM Systems	Equipment Manufacturer	Richmond Hill, Ontario	www.gemsys.ca
Geometrics, Inc.	Equipment Manufacturer	San Jose, California	www.geometrics.com
Geonics, Ltd.	Equipment Manufacturer	Mississauga, Ontario	www.geonics.com
Geophex, Ltd.	Equipment Manufacturer	Raleigh, North Carolina	www.geophex.com
Geophysical Survey Systems, Inc. (GSSI)	Equipment Manufacturer	North Salem, New Hampshire	www.geophysical.com
Geosoft, Inc.	Mapping Software	Toronto, Ontario	www.geosoft.com
GISCO	Equipment Manufacturer	St. Louis Park, Minnesota	www.giscogeo.com
Instrumentation GDD, Inc.	Equipment Manufacturer	Sainte-Foy, Quebec	www.gdd.ca
Interprex, Ltd.		Golden, Colorado	www.interprex.com
IRIS Instruments	Equipment Manufacturer	Orleans, France	www.iris-instruments.com
K. D. Jones Instruments		Normangee, Texas	www.kdjonesinstruments.com
Mitcham Industries, Inc.	Equipment Rental	Huntsville, Texas	www.mitchamindustries.com
SAGA Geophysics, Inc.	Equipment Rental	Austin, Texas	www.sagageo.com
Schonstedt Instrument Co.	Equipment Manufacturer	Kearneysville, West Virginia	www.schonstedt.com
Scintrex, Ltd.	Equipment Manufacturer	Concord, Ontario	www.scintrexltd.com
Zonge Engineering and Research	Equipment Manufacture and Software	Tucson, Arizona	www.zonge.com

5.2.2. Geometrics

Overview. Geometrics, Inc. of San Jose, California is one of the largest producers of geophysical field equipment in the world. Geometrics manufactures the OhmMapper CCR and Stratagem EH-4 magnetotellurics field recording systems.

OhmMapper. The OhmMapper CCR system is configured using a dipole-dipole type array (Fig. 9). A cross-section is generated by configuring the streamer with a electrode spacing. The streamer is dragged along a traverse on the ground to perform a profile-type measurement. Coaxial dipole cables are used as electrodes to capacitively induce current into the ground. The coaxial shield and the earth both act as conductors, and the cable insulation acts as the dielectric. The streamer is reconfigured with different electrode spacings, and the traverse is repeated. As electrode spacing increases, depth of penetration also increases. The result is a two-dimensional pseudo-cross section of apparent resistivity versus lateral position along the traverse, and versus electrode spacing, which is inverted using the RES2DINV software (Loke and Barker, 1996) to derive a true σ cross section.

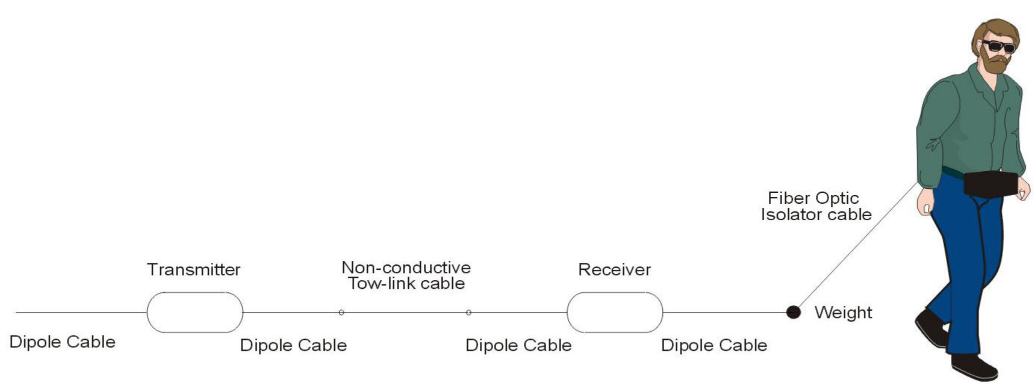

Fig. 9—Schematic illustration of the OhmMapper CCR system

Stratagem EH-4. Geometrics also manufactures the Stratagem EH-4 magnetotellurics system. The Stratagem system consists of galvanic stakes (or porous pots) for measuring the ambient electric field caused by lightning and solar wind, and induction coils for measuring the ambient magnetic field. Natural electromagnetic fields caused by lightning and solar winds typically span a bandwidth of approximately 10-90,000 Hz. Conductivity is calculated as a function of frequency, and this information is quickly inverted in the field to derive a sounding of σ versus depth. However, to achieve a reliable inversion results, the Stratagem uses an induction loop antenna system to artificially generate electromagnetic waves within a 1,000-70,000-Hz bandwidth where naturally occurring electromagnetic energy may be lacking. The induction loop antenna system resembles a large dome tent frame. By supplementing the ambient field, a more continuous conductivity-frequency curve is generated, which helps constrain the inversion and produce a more reliable sounding.

5.2.3. Geonics

Overview. Geonics, Ltd. of Mississauga, Ontario manufactures numerous instruments for terrain conductivity, TDEM, and VLFEM surveying. Terrain conductivity devices include the EM-31, EM-34, and EM-38 instruments. TDEM systems include the TEM47, TEM57, and TEM67 systems. Their VLFEM instrument consists of the EM16 and Tx27 systems.

EM-31 and EM38 terrain conductivity meters. The EM-31 and EM-38 are terrain conductivity devices with fixed coil spacings of 3.7 and 1.0 meters, respectively, and fixed operating frequencies of 9.8 and 14.6 kHz, respectively. Each device is operated at the push of a button, which allows for rapid data acquisition. Output from the instruments is a reading of average conductivity from the ground surface to a depth that is approximately equal to 1.5 or 0.75 times the coil spacing when operating in the vertical or horizontal dipole modes, respectively.

EM-34 terrain conductivity meter. The EM-34 is similar to the EM-31 and EM-38 meters, but coil spacings of 10, 20, or 40 m can be used with corresponding operating frequencies of 6.4, 1.6, and 0.4 kHz, respectively. The device can be used as a terrain conductivity instrument by using one coil spacing, or as an FDEM sounding instrument by varying the coil spacing.

*TEM47**, TEM57, and TEM67 TDEM systems.*** Geonics manufactures the PROTEM TDEM receiver, which can work with one of three different transmitter systems: TEM47, TEM57, or TEM67. The difference between the three transmitters is in the amount of power they supply and their depth of investigation. The TEM47 is a small battery-operated transmitter that operates over a bandwidth of 30-285 Hz with an input current of 3 amps into a 100 m x 100 m square loop, which can provide good resolution to a depth of 150 m. The TEM57 is a more powerful system that supplies up to 1.8 kW of power into a 300 m x 600 m loop over a bandwidth of 3-30 Hz. The TEM57 can be used to perform soundings to a depth of 500 m. The TEM67 transmitter is Geonics' most powerful. It supplies 4.5 kW of power to a 2,000 m x 2,000 m loop over a bandwidth of 0.3-30 Hz, and can be used to perform soundings to a depth of 1,000 m. The TEM67 replaces the older TEM37 model, which is no longer manufactured by Geonics. Inversion software must be purchased separately, and costs start at approximately $3,000.

EM16/Tx27 VLFEM System. The VLFEM system marketed by Geonics consists of the EM16 receiver and the Tx27 transmitter. The EM16 receiver is a small hand-held device that operates over a bandwidth of 15-30 kHz. If there is not sufficient ambient signal, the Tx27 transmitter can be used. The Tx27 operates at a frequency of 18.6 kHz and driving current of 0-2 amps, and uses either a 1-km grounded wire or a 500 m x 500 m square loop.

5.2.4. Geophex

Geophex, Ltd. of Raleigh, North Carolina manufactures the GEM-2 FDEM system. The GEM-2 represents the next generation of FDEM instruments because it uses a pair of closely spaced coils in a configuration similar to the Geonics and GISCO terrain conductivity meters. Traditional FDEM systems, such as the Apex MaxMin I-8, have relied on several pairs of coils, with each coil spaced a different distance apart and operated at a specific frequency. However, the GEM-2 takes advantage of a high dynamic range, internal electronics that cancel the primary signal, and coils with very high tuning frequencies, to develop a system where a single pair of closely spaced coils that can be used over a broad bandwidth to perform depth sounding. The GEM-2 is a portable hand-held device consisting of a transmitter and receiver coil spaced 5.5 ft apart on a boom. The coils are operated at frequencies ranging from 330-24,000 Hz. Apparent conductivity can be measured as a function of frequency, and this can be inverted to derive a sounding of σ versus depth to a depth of around 50 m.

5.2.5. GISCO

Overview. GISCO of Saint Louis Park, Minnesota offers EMG equipment for performing terrain conductivity and VLFEM surveying. Terrain conductivity meters are similar to those manufactured by Geonics, and include the CM-31, CM-32, and CM-138 models. GISCO also markets the Wadi VLFEM system.

CM-31, CM-32, and CM-138 terrain conductivity systems. The CM-31, CM-32, and CM-138 terrain conductivity meters each consist of a boom-mounted transmitter and receiver coil with a fixed coil spacing. Coil spacings for the CM-31, CM-32, and CM-138 are 3.7, 2.0, and 1.0 m, respectively. Operating frequencies for the CM-31, CM-32, and CM-138 are 9.8, 12.0, and 14.4 kHz, respectively. With these configurations and operating frequencies, the CM-

31, CM-32, and CM-138 instruments provide average conductivity from the ground surface to depths of 6, 3, and 1.5 m, respectively. Conductivity measurements are performed instantaneously at the push of a button.

WADI VLFEM System. GISCO also markets the WADI VLFEM system, which is manufactured by ABEM. The WADI operates over a bandwidth of 15-30 kHz, and can detect transmitter sources up to 10,000 km away.

5.2.6. GSSI

Geophysical Survey Systems, Inc. (GSSI) of North Salem, New Hampshire has recently discontinued its marketing of the GEM-300, a device that was similar to the Geophex GEM-2. However, they are currently developing the EMP-400 and EMP-600 instruments. Each instrument consists of a pair of coplanar coils spaced 4.0 and 6.0 ft apart, respectively. They can either be operated as terrain conductivity meters at one low frequency, or they can be operated at three frequencies and used as an FDEM profiler. Each device operates over a bandwidth between 1-16 kHz. However, as mentioned, the instruments are currently under development and not yet available. When they are available, their specifications may be slightly different, and cost figures will be available.

5.2.7. Scintrex

Scintrex, Ltd. of Concord, Ontario manufactures the ENVI VLFEM system. This system operates over a bandwidth of 15-30 kHz. The VLFEM system can also be purchased as part of a combined VLFEM-magnetics system.

5.3. Summary

Costs for each of the systems mentioned in this chapter are detailed in Table 8 on the following page. These costs include purchase costs, rental costs, training costs, and any associated software costs. Information is also provided regarding which method the instrument is applicable towards, and the achievable depth of investigation. Note that the costs presented in Table 8 are costs for the most basic versions of the equipment. Most manufacturers offer various upgrades to their instruments, with additional costs that could increase the overall system price by 10-20%.

Table 8--Cost summary for EMG equipment

Manufacturer	Model	Method	Depth of Investigation (m)	Purchase Costs[2] ($)	Rental Costs ($/wk)	On Site Training ($/day)	Software ($)
Apex	MaxMin I-8	FDEM	150	45540	1890	100+travel	2900
Geometrics	OhmMapper	CCR	20	25780	1475	800+travel	2700
	Stratagem EH-4	magnetotellurics	1000	61800	2556	800+travel	incl.
Geonics	EM16/Tx27	VLFEM	20	15950[3]	725	600+travel	incl.
	EM-31	terrain conductivity	6	22200	885	600+travel	incl.
	EM-34	terrain conductivity	60	26850	1135	600+travel	incl.
	EM-38	terrain conductivity	1.5	9275	500	600+travel	incl.
	TEM47[1]	TDEM	150	53750	2620	600+travel	3000
	TEM57[1]	TDEM	500	71000	3535	600+travel	3000
	TEM67[1]	TDEM	1000	92350	5330	600+travel	3000
Geophex	GEM-2	FDEM	7	19600	750	at cost	incl.
GISCO	CM-31	terrain conductivity	6	13850	(see note 4)	travel	incl.
	CM-32	terrain conductivity	3	12880	(see note 4)	travel	incl
	CM-138	terrain conductivity	1.5	11420	(see note 4)	travel	incl.
	Wadi	VLFEM	20	10020	(see note 4)	travel	incl.
GSSI	EMP-400	FDEM	2	(see note 5)	(see note 5)	(see note 5)	(see note 5)
	EMP-600	FDEM	3	(see note 5)	(see note 5)	(see note 5)	(see note 5)
Scintrex	Envi	VLFEM	20	9000	250	7000/5 days	2000

[1]Cost includes PROTEM receiver

[2]Actual costs for some systems may be 10-20% higher due to purchase additional coils, cables, power generators, and other miscellaneous items

[3]costs for the EM16 and Tx27 are $7,550 and $8,400, respectively

[4]GISCO does not rent its equipment

[5]These instruments are currently under development, so this information is not available

6. REFERENCES

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WisDOT Research

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Implementation of Research Results

Project Information	
Project Title: APPLICATION OF ELECTROMAGNETIC GEOPHYSICS (EMG) TECHNOLOGY TO SUBSURFACE INVESTIGATIONS	**Project ID: 0092-04-08 Today's Date: 06/23/2005**
Technical Oversight Committee (WHRP or COR):	**TOC Chair and Phone number: Dan Reid (608) 246-7946**
Project Start Date: 01/07/2004	**Approved Contract Amount: $29,824.00**
Project End Date: 06/30/2005	**Final Project Expenditures: $29,824.00**
Reference Final Report Draft Dated: 06/30/2005	
Principal Investigator: Michael E. Kailnski, Ph.D., P.E. **Organization: University of Kentucky**	**Phone: (859) 257-6117** **E-Mail: kalinski@engr.uky.edu**

Technical Oversight Committee Recommendations	
1. Check one of the two choices below: ☐ **Yes. We recommend changes to current practice based on <u>some or all</u> of the results of this report. The research was sound, and the report's conclusions appear to offer an advance over current practice.** ☐ **No. We do not recommend changes to current practice at this time. This approach does not appear fruitful OR future study is needed OR our objectives have changed, etc.**	
2. If implementation <u>is not recommended</u>, we suggest the following actions instead:	
3. If implementation <u>is recommended,</u> we suggest the following <u>specific</u> changes to current practice, detailed on the <u>attached work plan and timeline</u> (check applicable items): ☐ **Standard Specifications** ☐ **Quality Management Program (QMP) Specifications** ☐ **Facilities Development Manual (FDM)** ☐ **Highway Maintenance Manual** ☐ **Training, outreach** ☐ **Other (describe):**	
4. Approval of this implementation plan by the Technical Oversight Committee (chair on behalf of entire committee):	**Signature: Daniel D. Reid** **Date: 06/23/2005**
5. Approval of this implementation plan by the Council on Research (for COR approved projects):	**Signature(s):** **Date:**
6. Referral for development of detailed work plan and timeline to (check one):	☐ **WisDOT/Industry Technical Committee on:** ____________ ☐ **Other WisDOT policy body:** ____________

7. Approval of work plan and timeline by the WisDOT Bureau Director(s) responsible for the policies described in item #3 above:	**Signature(s):** **Date**
8. Acceptance by a project manager of the responsibility for completing these implementation efforts according to the attached work plan and timeline:	**Signature:** **Date:**

Rev. 4/8/01

Implementation Work Plan	
1. Project Title:	**2. Prepared by:**
1. Scope and objectives of implementation, including specific changes to WisDOT procedures.	
2. Estimated cost (if any) to implement.	
4. Expected benefits and how they will be measured (dollar savings, time savings, other).	
5. Possible pitfalls and how they will be avoided.	

Implementation Timeline (Gantt Chart)												
Tasks/Person Responsible												